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Novel Ultrasound Scintillator

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ABSTRACT:
This development project addressed the need for a faster, less expensive method of transmission ultrasound. It utilized the principle of frustrated total internal reflection to transduce acoustic pressure into optical modulation. These data were acquired an entire 2D plane at a time. This report describes the modeling and verification of a final sensor design.

INTRODUCTION: Ultrasound imaging is used to inspect parts, monitor processes, and diagnose people. Soon after x-ray CT was invented, attempts were made to do the same kind of imaging with ultrasound. One of the many problems encountered in this pursuit was the difficulty of acquiring the necessary data in a timely fashion. Other problems included the tendency of ultrasound not to travel in straight lines, and to require a couplant between source, object, and sensor.

The existence of these problems is unfortunate, considering that 3D volumetric imaging by ultrasound would be quite useful for screening for breast cancer. Consider the advantages: no ionizing radiation, no compression, and no toxic developing solutions or film. Of course, at present the only way to get the information necessary to do this kind of imaging is to use arrays of piezoelectric sensors (and either multiplex them in time or have multiple copies of the necessary electronics to read them). This is expensive, and another way is needed to get these data. The sensor we developed addresses these problems.

Our new sensor uses the classical optical phenomenon frustrated total internal reflection (FTIR) to make the incident ultrasonic wave modulate a beam of light, which is then acquired by a camera and computer. A sequence of images, each taken at a different source acoustic phase, enables us to reconstruct the ultrasonic phase and amplitude over an entire 2D surface.

In this paper we detail the development and design of our optically parallel ultrasound sensor.

Optics

Frustrated total internal reflection is a consequence of the wave nature of light[1]. When light moves from a slow medium to a fast one, there is a critical angle, $\theta_c = \sin^{-1}(n_2 / n_1)$ (where n_1 is the index of refraction of the slow medium and n_2 is the index of the fast medium), beyond which the light is totally reflected. However, an evanescent wave extends a short distance into the fast medium (approximately one wavelength), and if another piece of slow medium intercepts this evanescent wave, some of the light tunnels across the gap (see figure 1). How much light tunnels is a function of the angle of incidence, the indices of the media, and, most importantly from our point of view, the size of the gap.

We exploited this effect to build an array of acoustic pixels. Each acoustic pixel is comprised of a thin silicon nitride membrane suspended on short gold walls over an optical substrate. The gap between the membrane and the optical substrate is filled with air (see figure 2). The entire assembly is immersed in the ultrasonic couplant. When an ultrasonic pressure wave impinges on the acoustic pixel, the membrane deflects, causing a change in the amount of light reflected from the total internal reflection surface of the acoustic pixel. An entire array of acoustic pixels can be used to modulate a beam of light.

The information we desire from this sensor is the phase and amplitude at each acoustic pixel. To obtain this information we illuminate the sensor with ten sequences of optical pulses, each sequence timed to act as a strobe light at a specific acoustic phase (see figure 3). We extract the phase and amplitude at each pixel by fitting the intensity at that pixel through the sequence to the form $I = B + A \sin(2\pi i / 10 + \phi)$, where I is the intensity, B is the background, A is the amplitude of the sinusoidal variation, i is the index of the image in the sequence, and ϕ is the phase of the variation.

The optical train of this device is as follows. We illuminate the sensor using an LED, the light from which is homogenized, polarized, and collimated. We acquire the reflection from the sensor using a CCD still camera.

Acoustics

The inspection technique we are interested in is transmission ultrasound. In this modality, an acoustic source sends out pressure waves through a couplant (such as water, oil, or medical ultrasound gel) to the object of interest. The pressure waves are transmitted through the object, along the way being changed in amplitude and phase. The pressure wave emerges from the object of interest and travels, via the couplant, to an acoustic sensor. The sensor determines the acoustic phase and amplitude (either at a point, on a line, or in a plane). The sensor we are developing will measure the acoustic phase and amplitude an entire plane at a time.

Our sensor works because the pressure wave causes the flexing of a membrane, vibrating it with a phase and amplitude that are a function of that wave.

In designing our sensor, we needed to have a membrane with a frequency response high enough so that it could be made to vibrate at the frequencies of interest to us (approximately 1MHz).

PROGRESS:

Modeling

We began our work on this project by modeling as many of the systems and processes as possible. We used TSARLITE to model the optical elements of the sensor (Frustrated Total Internal Reflection), DYNA3D to model the acoustic responses of the membranes and their supports, and a modification of BEEMER to model the imaging system as a whole.

By using TSARLITE, we were able to determine the ranges where we could expect FTIR to be useful, and bounded the permissible thickness of the membrane and the heights of the supports it would stand upon. This aspect of the modeling was performed to make certain that we would be able to engineer to the physical phenomenon we were using.

The modified BEEMER program was used to examine the issues that will arise when we use the sensor for diffraction tomographic imaging. It was used to model the tomographic data acquisition processes, as well as a variety of reconstruction algorithms.

The simulation program which we used most was DYNA3D. We used this program to model our first sensor design, a membrane suspended on an array of posts. DYNA3D showed us that this design had neither the sensitivity nor the frequency response necessary to allow us to acquire the data we needed. Guided by our simulations, we developed a more responsive design, a set of resonant membranes suspended on walls (see figure 2). Simulation showed this design was responsive and sensitive, but had problems with crosstalk and a drift of the resonant frequency as a function of hydrostatic pressure (see figure 4). Further simulation allowed us to modify the design so as to greatly reduce crosstalk (see figure 5).

Simulation eliminated the need to experiment blindly, but we still needed to do experiments to verify that the simulations were correct, and get proof of principle results. To do these experiments we built a test system.

Verification

The test system we built consisted of: the test membrane, a tank with an acoustic source, and the optics. The test membrane was designed to allow us to examine the responses of a wide range of membrane resonator sizes to variations in hydrostatic pressure. The rest of the system was designed to make all of the parameters of interest easily available for manipulation.

The test membrane consists of a 1 cm by 1 cm membrane of silicon nitride, supported by gold walls, held in a silicon frame. The gold walls are patterned as shown in figure 6. On the left hand side of the test membrane are alternating rows of 60 acoustic pixels ranging in size from 20 microns on a side, up to 80 microns on a side. On the right hand side of the test membrane only half of the rows are populated with acoustic pixels. The reason for the wide range in size is evident from figure 4. We suspected that only acoustic pixels that were at the exact resonant frequency would be sensitive enough to modulate the optical input, and so attempted to include all pertinent sizes. In addition to the wide range in resonator sizes available we had membrane fabrication parameters available for modification as well: membrane thickness and gold wall height.

The remainder of the system is illustrated in schematic form in figure 7. The oscillator provides a 1 MHz signal, which is amplified and fed through the power meter to the acoustic source in the water tank. The same signal goes to the pulse generator, which in turn excites the optical source as a strobe light. The pulse generator output and the oscillator output are both fed to an oscilloscope in order to allow the user to place the optical pulse at any point in the acoustic phase. The optical pulses are homogenized, polarized, collimated, and fed through the prism to the sensing surface, and the reflected light is captured by the camera and saved in the computer. The user has control over the oscillator frequency, the amplifier gain, the camera exposure time, the optical pulse width, amplitude, and placement in the acoustic phase, and the depth of the water in the tank.

This is the procedure followed during a typical experimental run: The water tank is filled to the desired depth, and the acoustic power level, camera exposure time, optical pulse width, and optical pulse amplitude are set. Four sequences of ten images are acquired, each with the optical pulse occurring at a different acoustic phase.

We learned a great deal using the test system, most importantly that: 1) we can engineer to the sizes and tolerances necessary to utilize the physical phenomenon, 2) we can extract phase and amplitude data at each acoustic pixel from sequences of images, 3) the resonances are so broad as to make acoustic pixel size non-critical, and 4) hydrostatic pressure causes little change in membrane response.

After performing numerous experimental runs we were able to arrive at an optimal set of design parameters for the final sensor.

FUTURE WORK:

We have completed the design for the final sensor. The final sensor is currently in the process of fabrication. Although our LDRD funding was discontinued, in the next fiscal year we will complete the construction of our final sensor, calibrate it, and use it to collect phase and amplitude data through a variety of test subjects. Initially we will only make 2D transmission ultrasound images, but ultimately we will generate volumetric images of 3D objects using data from this sensor to feed a diffraction tomography code.

This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

REFERENCES:

1. Pochi Yeh, *Optical Waves in Layered Media*, John Wiley and Sons, 1988.

FIGURE CAPTIONS

Figure 1. (a) In total internal reflection, light trying to exit the slow medium at an angle higher than the critical angle will be completely reflected. (b) In frustrated total internal reflection, the evanescent wave that extends into the fast medium overlaps another piece of slow medium, and some of the light tunnels across the gap. (c) The amount of light that tunnels through the gap is very sensitively dependent on the size of the gap.

Figure 2. An acoustic pixel is a thin membrane suspended over an optical substrate by gold walls. There is an air gap between the membrane and the optical substrate, and the acoustic pixel is exposed to water. An ultrasonic pressure wave moving through the water will cause the membrane to vibrate, changing the air gap enough to modulate a beam of light reflected from the total internal reflection surface of the optical substrate.

Figure 3. The illumination of the optical substrate occurs at particular times during the acoustic wave. This causes the optical beam to act as a strobe light. A sequence of ten images allows us to deduce the motion of each acoustic pixel through the acoustic wave, and thus the pressure and phase of the acoustic pixel excitation.

Figure 4. This graph shows how the resonant frequency of a set of acoustic resonators varies with the hydrostatic pressure load.

Figure 5. (a) All of the acoustic pixels in this simulation have the same resonant frequency. An excitation of the rear left pixel spreads to all the surrounding acoustic pixels. (b) Staggering the sizes of the acoustic pixels greatly reduces the spreading of energy (cross-talk).

Figure 6. This is a schematic of the pattern of acoustic pixels in the test membrane. On the left are alternating rows of 60 acoustic pixels ranging in size from 20 microns on a side, up to 80 microns on a side. On the right only half of the rows are populated with acoustic pixels.

Figure 7. The test system. The oscillator drives the amplifier and pulse generator with a 1 MHz sinusoid. The acoustic source insonifies the test membrane which is illuminated with 50 nanosecond optical pulses strobing at a user specified acoustic phase. Images of the membrane are acquired by the camera and stored and processed in the computer.

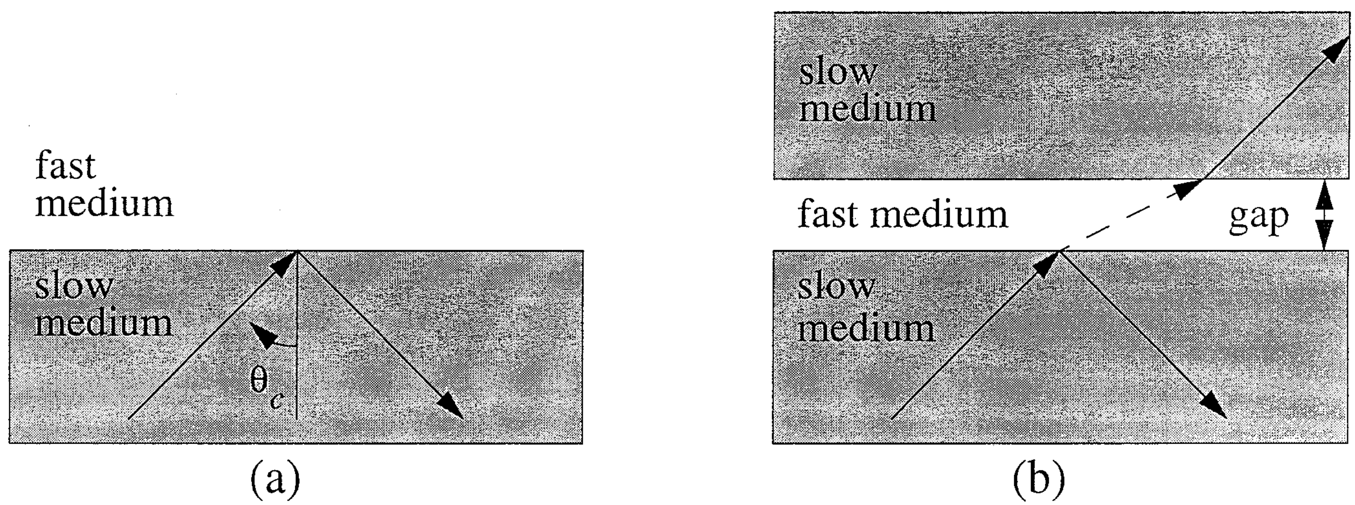

fast
medium
slow
medium
θ_c
(a)
slow
medium
fast medium
gap
slow
medium
(b)

figure 1

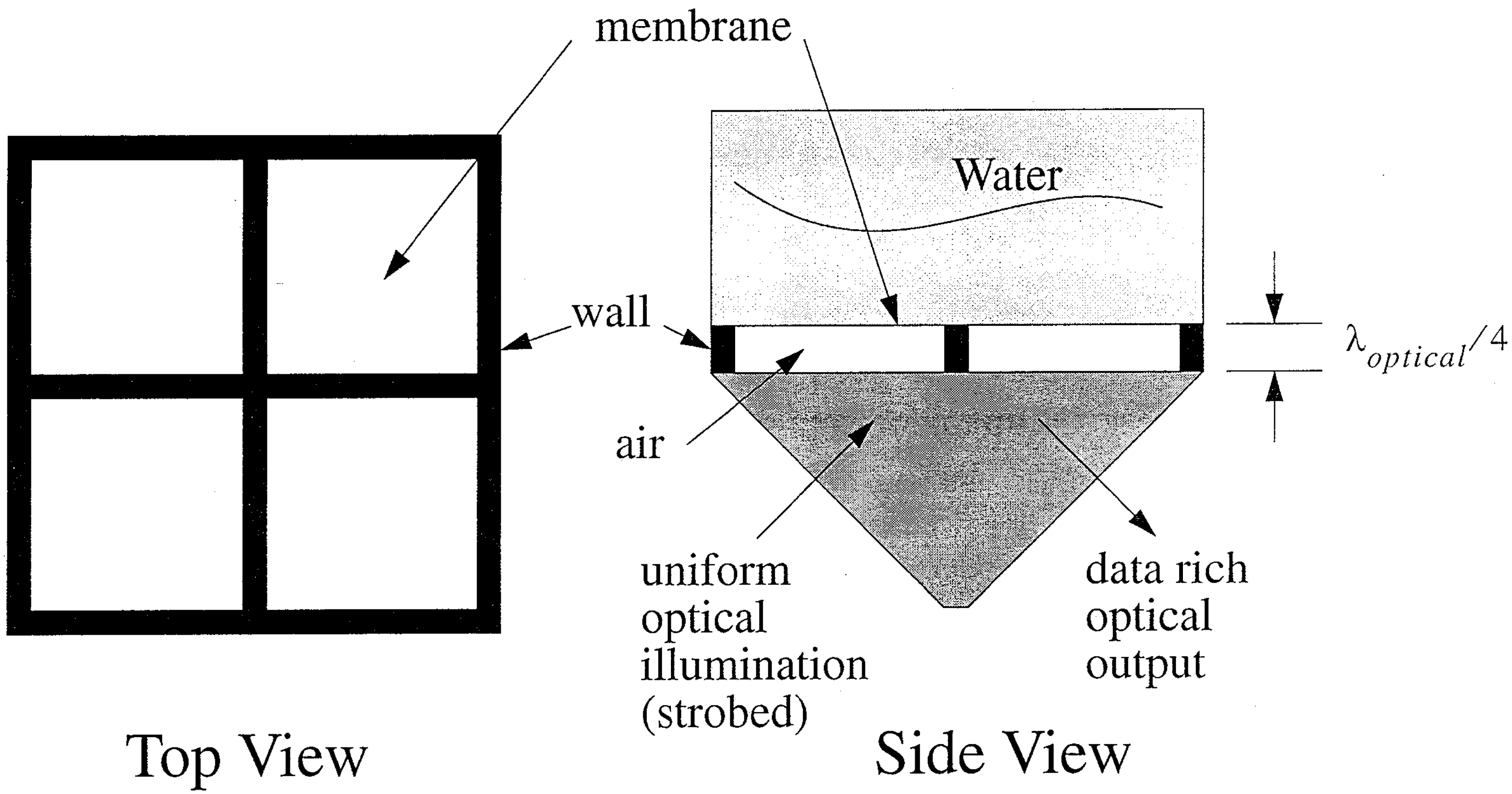

membrane
Water
wall
air
$\lambda_{optical}/4$
uniform optical illumination (strobed)
data rich optical output
Top View
Side View

figure 2

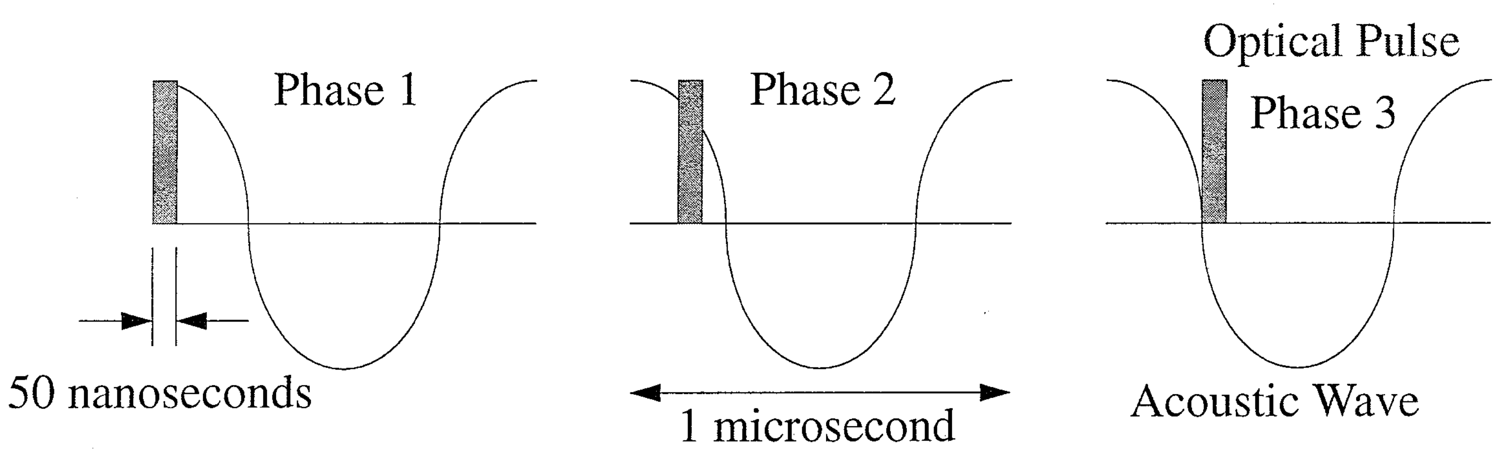

Optical Pulse
Phase 1
Phase 2
Phase 3
50 nanoseconds
1 microsecond
Acoustic Wave

figure 3

Resonant Frequency vs Pressure

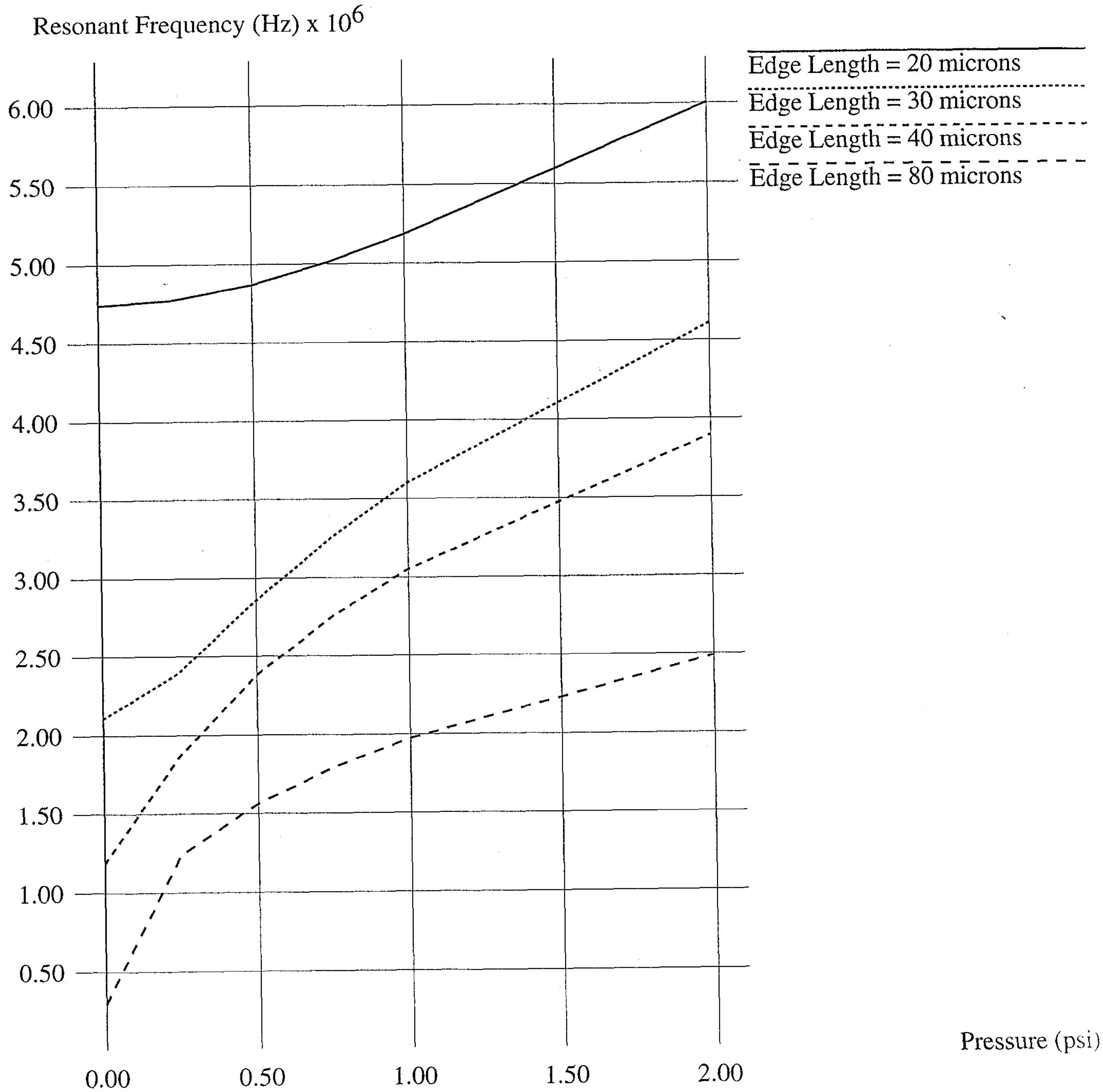
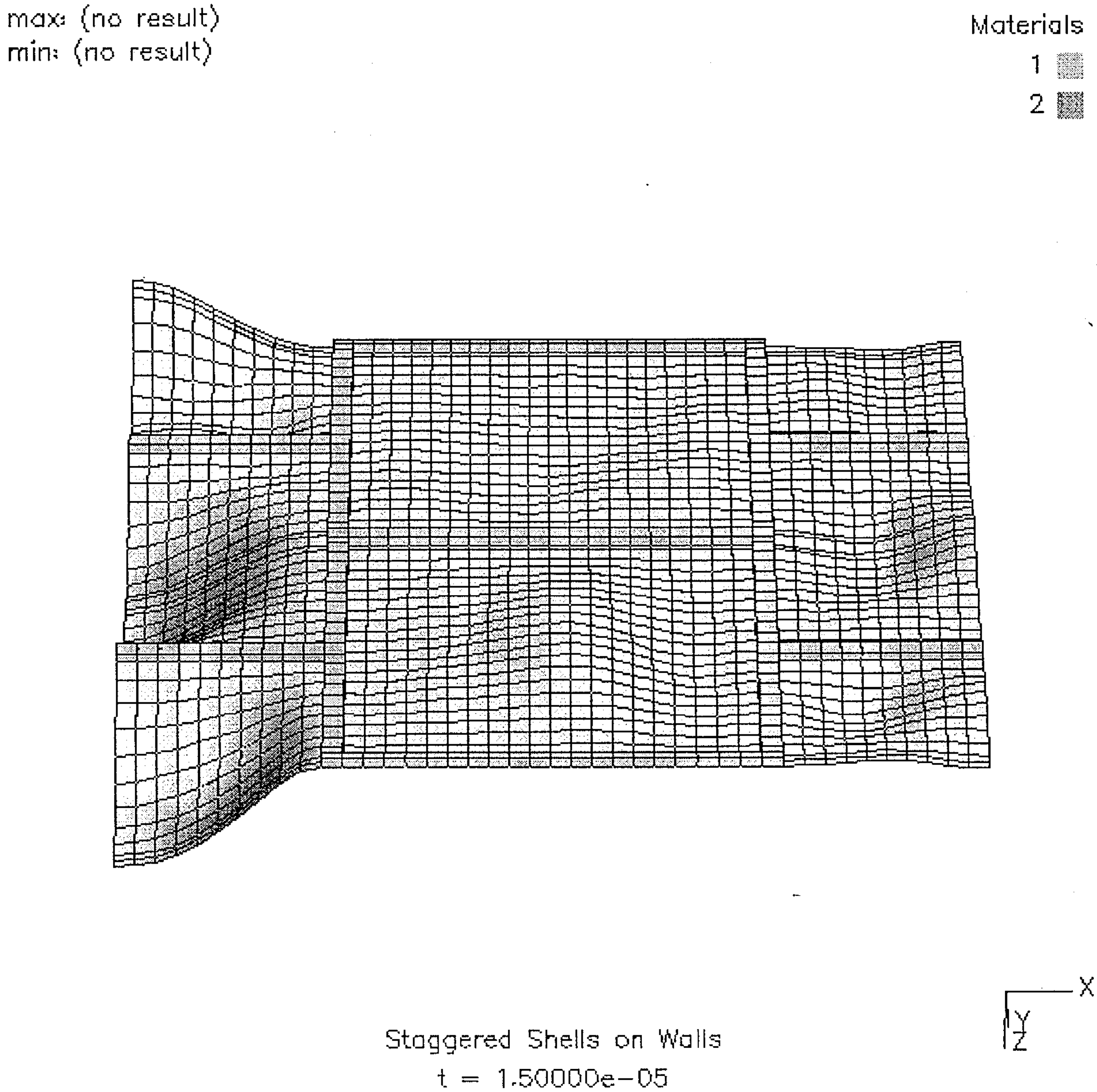


figure 4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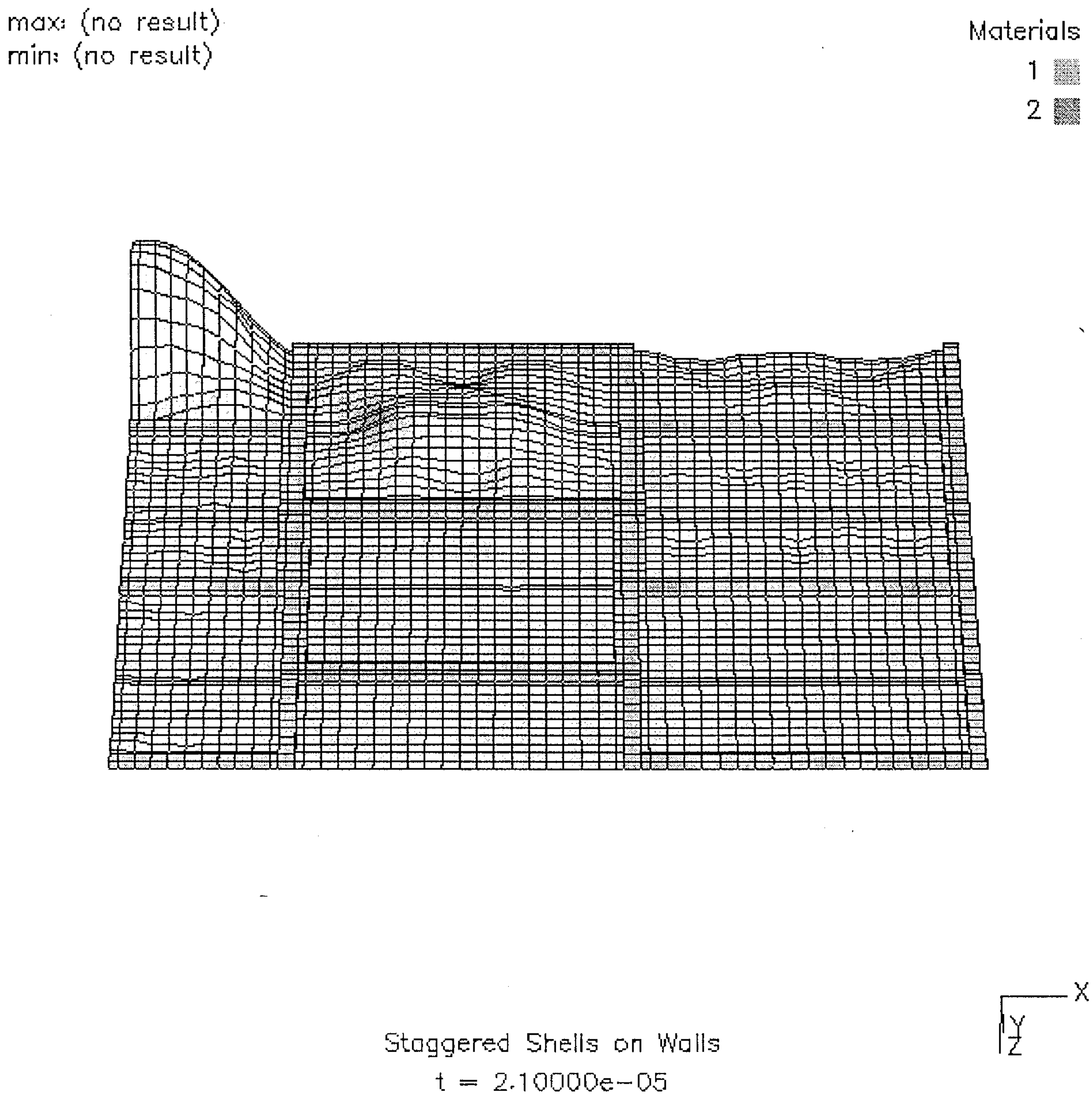
min: (no result)
Materials
1
2
X
Y
Z
Staggered Shells on Walls
t = 1.50000e-05

figure 5a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Materials
1
2
X
Y
Z
Staggered Shells on Walls
t = 2.10000e-05

figure 5B

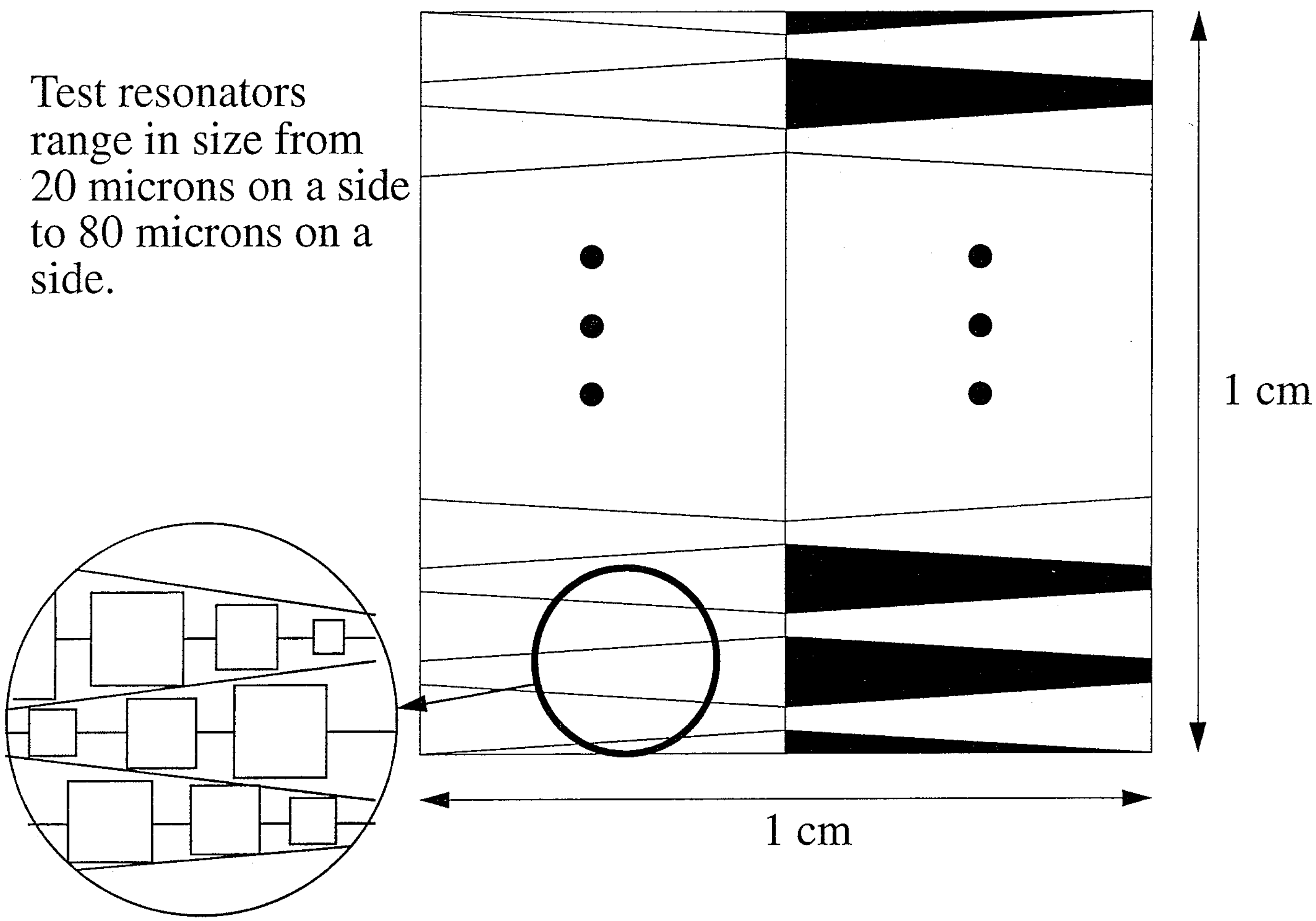
Test resonators
range in size from
20 microns on a side
to 80 microns on a
side.
1 cm
1 cm

figure 6

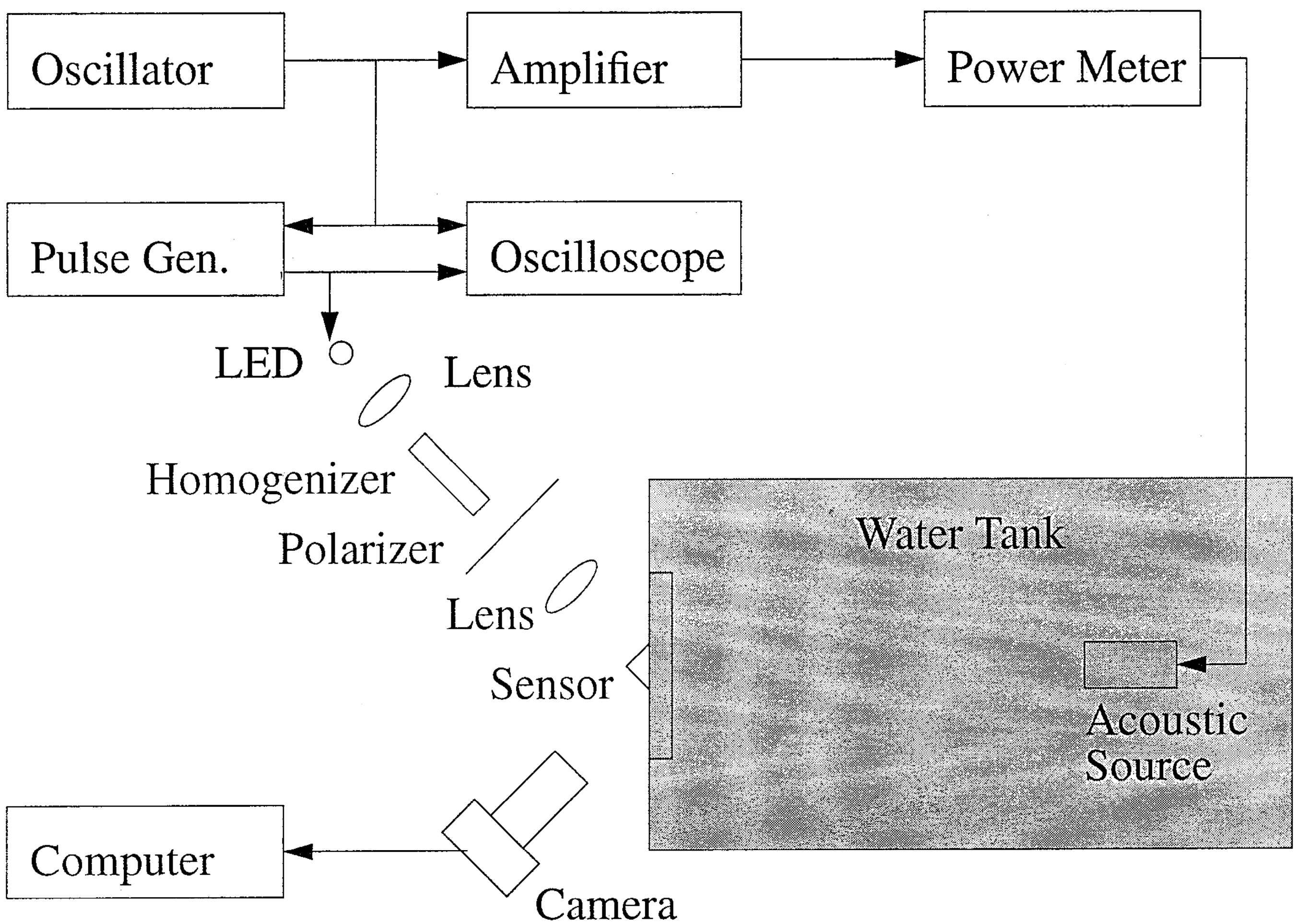
Oscillator
Amplifier
Power Meter
Pulse Gen.
Oscilloscope
LED
Lens
Homogenizer
Polarizer
Lens
Water Tank
Sensor
Acoustic Source
Computer
Camera

figure 7